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FLOW BEHAVIOUR TO DETERMINE THE DEFECTS OF GREEN PART IN METAL INJECTION MOLDING

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ABSTRACT

The paper describes author's work on the investigation of the molding flow behaviour to determine the defects of green part in metal injection molding (MIM) using powder of carbonyl iron (CIP-S-1641) mix with polymer-based binder, *Hostamont EK583* at different powder loadings. Rheological properties of the feedstock were presented in this paper. Results show that all feedstock have good pseudoplastic behaviour, which is suitable to be injection molded. Since the flow behaviour of the feedstock in molding cannot solely depends on the rheological test especially in control the quality of green part, this paper also investigate the molding practice via using MOLDFLOW software and compared with the actual experiment. After molding practice the results shows some defects still occurred on green part and it has been control by proposed the optimum molding parameters such as injection temperature and injection pressure.

Keywords: Metal injection Molding, feedstock, rheology, defects, MOLDFLOW.

1 INTRODUCTION

Metal injection molding (MIM) is a net-shape process to produce relative small metal parts with high complex geometries. The MIM process consists of four steps such as mixing, injection molding, debinding and sintering (German and Bose, 1997, Binet *et al*., 2003). Small-sized metallic powder is initially mixed with a wax-polymer binder to form a homogeneous feedstock and the feedstock is shaped by a mold. After removal the resulting green part from the mold, the wax-polymer binder is removed by heating and sintered (solid-state diffused) in a controlled atmosphere furnace in similar way to traditional powder metallurgy (Liu *et al.,* 2005; Quinard *et al.,*2008). MIM products are various and range from consumer products, office equipments, medical instrument and automotive components to industrial processing equipment. The viscosity of feedstock plays a very important role in MIM process as it is required for allowing the particles flow into the cavity. Mold filling with the MIM feedstock is dependent on viscous flow of the mixture into the cavity (Bilolov et al., 2006). This required specific rheological characteristic (Khakbiz *et al.,* 2005). MIM feedstock has been often characterized rheologically by capillary rheometer (Jamaludin *et al.,* 2008). Rheological properties of both binder and feedstock are one of the key features to produce a green part with uniform density and no defects (Huang et al., 2003). This paper briefs us the rheological properties and investigates the viscosity of MIM binder and feedstock. It is sometimes cannot solely depend on the rheological test until injection, debinding and sintering process are carried out. For example, study conducted by Iriany (2001) which emphasized only on the characterization of the feedstock through rheological testing, the amount of palm stearin binder that she had found must not exceed 45wt% in order to avoid binder separation. Meanwhile research conducted by Subuki (2005) had reported that the maximum amount of palm stearin binder was 70wt% and the sample was successfully sintered without any difficulties and defects on the sintered parts.

So in this research, further improvement of the metal feedstock characteristics is obtained by optimize the process parameters to produce MIM parts without defects and with required mechanical properties by using experimental tests coupled to simulations methods. The flow simulations were consequently performed by employing the same commercial software developed for thermoplastics, MOLDFLOW with the correct definitions of metal feedstock properties.

2 EXPERIMENTAL PROCEDURES

The powder used for this study was carbonyl iron (CIP-S-1641) with the mean particle size of 4µm. It's provided a high packing density which is optimal for injection molding due to its small particle size. The binder used was a wax-based ready-made binder, Hostamont EK583 supplied by Clariant which consists of polyolefin wax and polyethylene co-polymer. Mixing was carried out using a sigma blade mixer to prepare the MIM feedstock at three different solid loading 54%vol, 56%vol, and 58%vol. The mixing temperature was set at 175^{o}C for duration 2 hours. The viscosity of both binder and feedstock was measured by using a capillary rheometer model Shimadzu CFT-500D at different temperature. The feedstock was then injected using injection molding machine ARBURG 850-210 A 320D and the results were compared by the results from MOLDFLOW simulation software. Table 1 shows properties of the feedstocks that will be used as material data in MOLDFLOW to obtain accurate flow simulation.

Table 1: Properties of Feedstock

Powder Loading	Thermal Conductivity K (W/m K)	Density ρ (kg/m^3)	Melting Temperature ^{o}C
54% vol	2.8606	4553.77	78.4
56 %vol	2.9081	4664.42	76.9
58 %vol	3.0927	4771.24	76.1

Table 2: Viscosities of Hostamont EK 583 (Pa.s) at different temperature

Pressure	Temperature (^{o}C)					
(MPa)	140	150	160	170	180	190
0.4903	4.631	3.846	1.344	1.289	1.487	1.266
0.9807	3.326	2.896	2.055	1.910	1.903	1.895

Table 3: Viscosity of MIM feedstock (Pa.s) at different solid loading

Solid loading (%vol)	Applied Pressure (MPa)	Temperature (^{o}C)				
		150	160	170	180	190
54	0.09807	336.2	249.7	202.1	172.6	139.8
	0.1716	205.9	140.2	112.4	93.64	78.51
	0.2452	143.6	92.52	76.08	65.49	53.44
56	0.09807	428.1	295.3	245.1	211.7	147
	0.1716	262	164.1	136.6	114.3	92.22
	0.2452	182.6	108.2	88.48	75.8	62.55
58	0.09807	662.9	471.5	402.4	360.2	228.2
	0.1716	392.7	275.1	226.7	203	133.4
	0.2452	284.8	181.8	160.7	120.6	91.64

3 RESULTS AND DISCUSSION

3.1 Rhological test

Binder should posses a lower viscosity than feedstock. The viscosity of MIM feedstock is quite higher than that of binder because of the high volume fraction of powder particles. At injection molding temperature, the viscosity of MIM binder is usually less than 10 Pa.s, while for MIM feedstock may vary from 10Pa.s to 1000Pa.s with shear rate at the same temperature (German and Bose, 1997, Yimin *et al.,* 2007). Table 2 lists the viscosity of ready-made wax-based binder, Hostamont EK583 at different temperatures. The results show that the viscosity of the binder decreases with temperature analogous to rheological behavior of pseodoplastic fluid. At the same temperature, the viscosity changes regularly with the increasing of pressure. Table 3 shows the relation of the viscosity of the feedstock at different temperature and different pressure, which indicate the flowability of MIM feedstocks. The lower the value of viscosity, the easier it is for a MIM feedstock to flow (Yimin *et al*., 1999). A MIM feedstock is generally considered to be a pseudoplastic fluid, which indicate a decreasing of viscosity with increase shear rate and temperature. For pseudoplastic fluid, it can be expresses by the equation below:

$$\tau = k\gamma^n \quad (1)$$

where τ is shear stress, γ is shear rate, *k* is coefficient and *n* is shear strain sensitive exponent which is less than 1.

The value of n indicates the degree of shear sensitivity. The higher the value of n, the longer the viscosity changes with shear rate. So, it is recommended to select the MIM feedstock, which possess a higher value of n to ensure the viscosity decreases slowly with increasing shear rate during injection process. The relation between logarithm of shear stress and shear rate is shown in Figure 1.

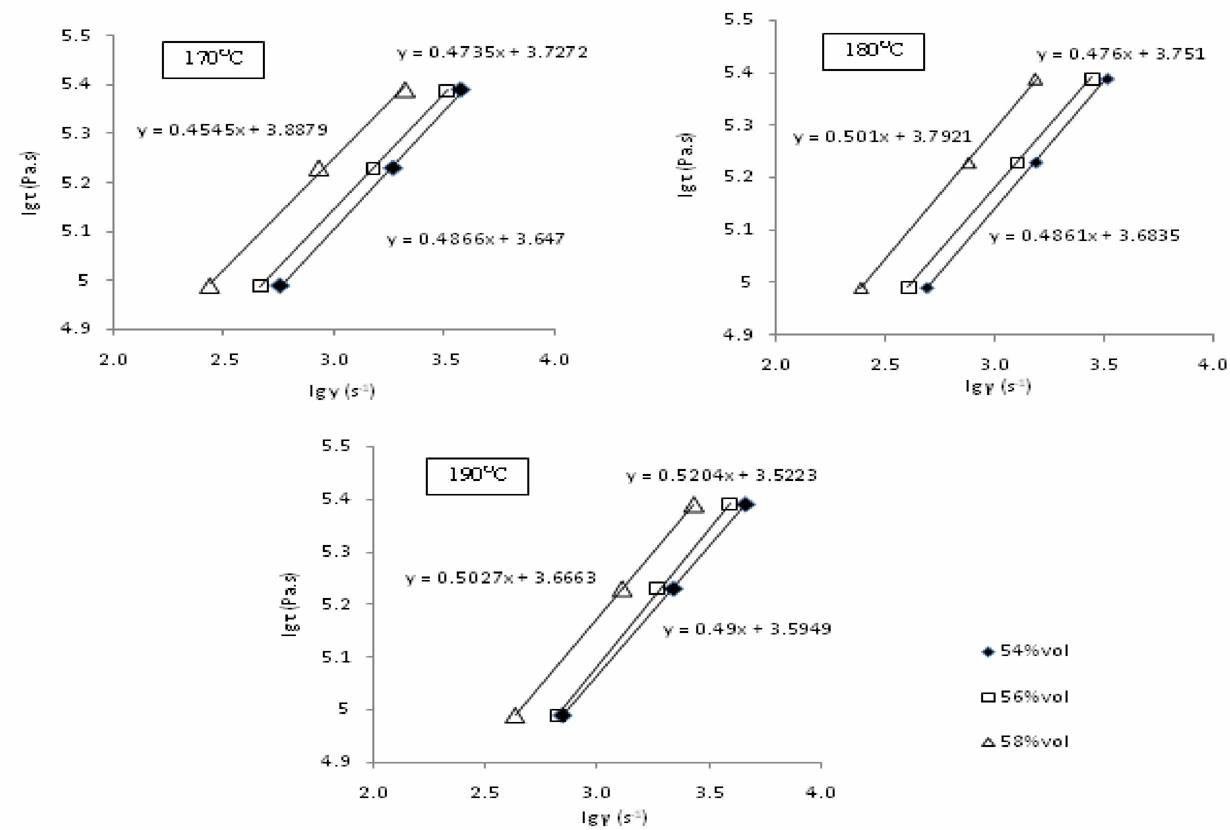

Figure 1: The relation between shear stress and shear rate of feedstock at different temperature

There is only a slight different of the value of n, which ranged between 0.4545 to 0.5204, due to the same binder component. However many publishers (German and Bose, 1997, Yimin *et al*., 1999) considered the higher value of n, which means a low sensitivity of viscosity at increasing shear rate. The high shear sensitivity is important especially producing complex and intrinsic parts. The behaviour of MIM feedstock is thermally activated, where the viscosity, η is expressed by an Arrhenius equation as below:

$$\eta(T) = \eta_o \exp(E/RT) \quad (2)$$

where E is the flow activation energy, R is the gas constant, T is temperature and η_o is reference viscosity. The value of E is the activation energy for viscous flow and large value indicate a high sensitivity of viscosity to temperature change. It means that if the value of E is low, the viscosity is not so sensitive to temperature change. Therefore, by selection of the feedstock with low E value during molding process, the temperature effect does not cause sudden viscosity change that could cause molding defects such as cracking, distortion and weldline formation. At low temperature the feedstock viscosity is too high for standard molding conditions, while at high temperature results in binder separation that leads to defect of the injected part. Figure 2 shows the logarithm of the viscosity against temperature with the value of E for every feedstock: $E_{54\%vol}$ = 1810 kJ/mol, $E_{56\%vol}$ = 2101kJ/mol and $E_{58\%vol}$ = 2038kJ/mol. It means that the feedstock of 54%vol which having a lower value of E is not too sensitive to temperature compared to others. Eventhough rheological test has been carried out, it is difficult when translating the data during injection molding practice. It is caused by other conditions that might influenced the MIM feedstock, such as feedstock size, machine conditions and environment. However, the data would give some insights on the scope of the parameter condition to be applied during injection molding practice.

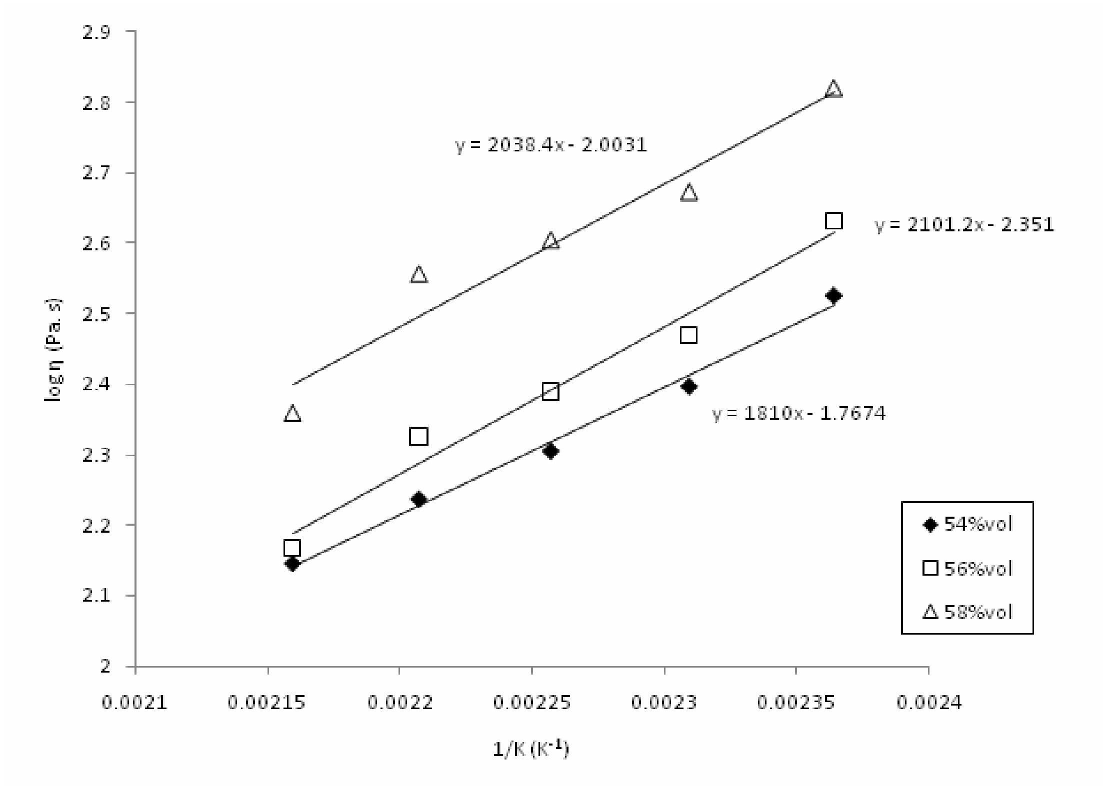

Figure 2: The relation between viscosity of feedstock and temperature

3.2 Numerical simulation and experimental tests

Comparison between simulation and actual molding results are shown in Figure 3. As the figures shows, the simulation well predicted the filling progression. Figure 3(a) shows short shot defect when feedstock of 54%vol. was injected at temperature of 150°C and injection pressure 900 bar. Short shot was caused by several reasons: low barrel temperature, low mold temperature or insufficient shot size.

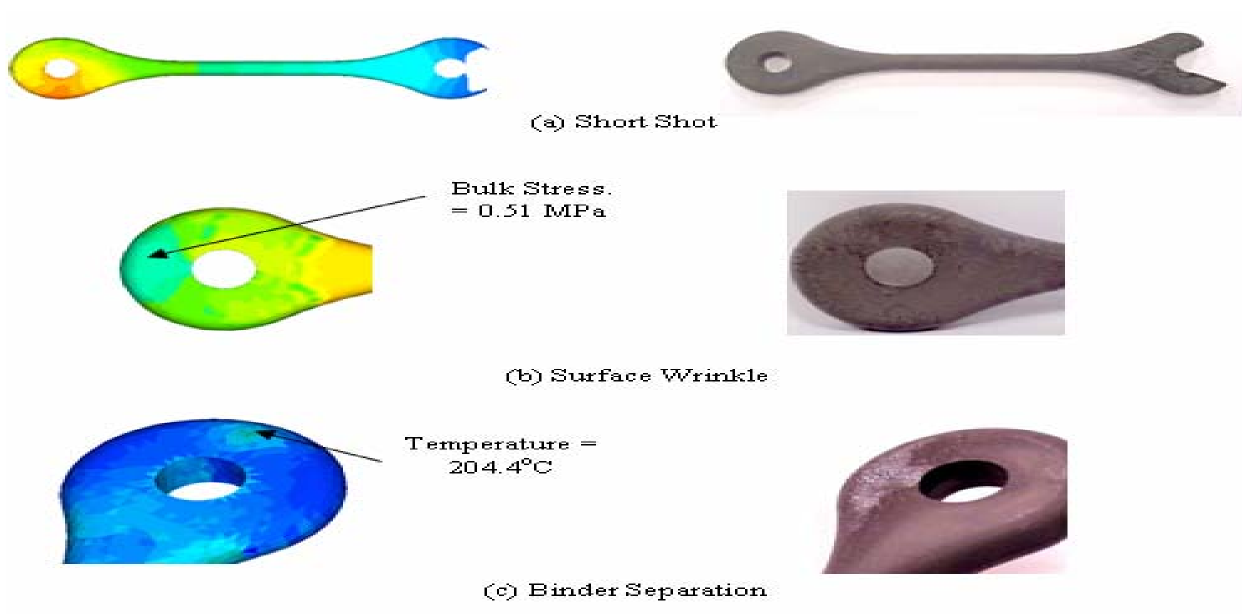

Figure 3: Defects in Actual Molding Compared with MOLDFLOW Result

It is similar what is predicted by simulation compared to the experimental. At slow injection speed, short shot occurred because of the short freezing time of MIM feedstock. During injection molding, surface wrinkle is one of the most frequently found defects. Figure 3(b) shows surface wrinkle of 56%vol. It is caused due to the excessive pressure at a low temperature condition. High packing pressure pushes feedstock through the gate to compensate the reduced volume in the cavity. Feedstock does not flow easily into the cavity at a low temperature even by high pressure. Then, semi solid deformation occurs, creating surface wrinkles of the part. This actual surface wrinkle can be compared with the result of bulk stress in MOLDFLOW. Another critical defect in MIM process is binder separation as shown in Figure 3(c). This kind of defect cannot be detected in conventional plastic injection molding. Binder separation occurred when injection was applied at high pressure and high temperature. If we compared from MOLDFLOW simulation temperature result, it shows that temperature rise too high and reach at 204.4^{o}C. Since the defects are still occurred even rheological results exhibit a good flow , a conceptual design has to be plotted to optimize the injection parameters process as shown in Figure 4.

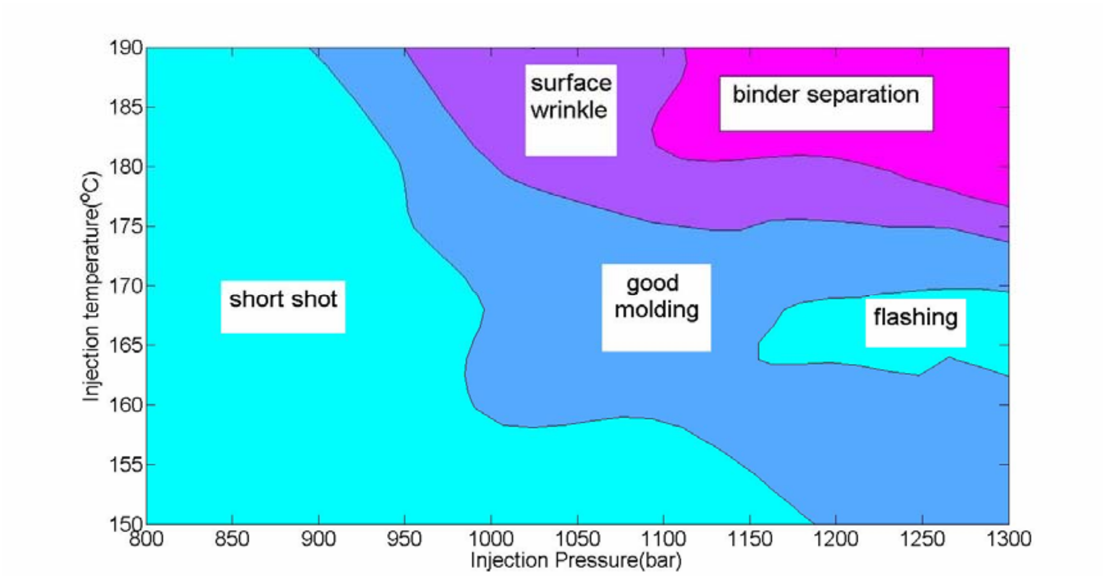

Figure 4: Optimization for injection molding parameter

4 CONCLUSIONS

It can be concluded that the viscosity plays a big role in predicting the injected parts by considering the shear sensitivity, *n* and the flow activation energy, *E*. All the feedstocks have pseudoplastic characteristic, where the viscosity decreases with shear rate at certain temperature. The MIM feedstock should permit higher shear sensitivity and lower flow activation energy, which is advantageous to MIM process. Result of bulk stress and temperature distribution in MOLDFLOW analysis could be used to control the defects of surface wrinkle and binder separation during actual molding. Good agreement between simulation and experiment results will provide a guideline to predict the actual molding for cavity of the green parts.

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